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HYDROGEN'S ROLE IN GREEN ECONOMY: OPPORTUNITIES AND CHALLENGES IN SELECTED EUROPEAN COUNTRIES

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Abstract: *Hydrogen is an important element in the transition to a green economy, with its potential to play a key role in the decarbonization of industry and transport within the European Union. The aim of this article is to analyse the differences in hydrogen production and consumption between selected European countries in the context of their economic maturity. Based on data from 2020 to 2023, a quantitative analysis was conducted including variables such as hydrogen production and consumption capacity and GDP per capita. Using non-parametric tests (Kruskal-Wallis, Dwass-Steel-Critchlow-Fligner), statistically significant differences were identified between groups of countries with high and low levels of hydrogen infrastructure development. The results confirm that higher economic performance of countries is closely related to a more developed hydrogen economy. The discussion highlights the importance of investments, regulatory frameworks and technological innovations in the implementation of hydrogen solutions. The article also identifies the challenges faced by less developed countries and recommends an approach based on support and cooperation within the EU.*

Keywords: *European Union, Green Economy, Green Logistics, Hydrogen, Non-parametric tests, Sustainability.*

1 INTRODUCTION

The transition to a green economy is one of the key challenges of the 21st century, with the decarbonisation of industry and transport among its main priorities. Hydrogen, as a flexible energy carrier, is gaining increasing attention for its potential to contribute to reducing greenhouse gas emissions, diversifying energy sources and supporting innovation in the field of sustainable mobility. In this context, the European Union has set ambitious targets for the production and use of hydrogen, which, however, encounter differences in the economic and technological readiness of individual Member States.

The aim of this study is to analyse the relationship between the economic performance of countries and the level of development of hydrogen infrastructure, specifically in the area of hydrogen production and consumption capacity and the number of registered hydrogen vehicles. Special emphasis is placed on identifying differences between countries with a high and low level of economic development, while the approach chosen in the work allows identifying potential disparities and formulating recommendations for EU policy in the area of supporting the development of hydrogen technologies.

1.1 Literature review

Hydrogen has been at the forefront of discussions on Europe's energy transition in recent years as a key element in the fight against climate change. Although plans are ambitious and investments are increasing, this energy carrier remains at the beginning of its journey towards mass use (Abbasov, 2024). The European Union has set ambitious goals to achieve 10 million tonnes of domestic production of green hydrogen and a further 10 million tonnes from imports by the end of this decade, but current production of clean hydrogen remains well below these values. Studies show that for hydrogen technologies to be successfully implemented, obstacles must be overcome technological, economic and regulatory barriers. The so-called hydrogen valleys and national initiatives in selected European countries must play a key role in this (Sadik- Zada, 2021).

1.1.1 Concrete steps under the European hydrogen strategy

The European Commission plans to present an EU hydrogen strategy together with a strategy for the integration of European energy systems with the aim of connecting the various energy sectors. The primary steps the EU is considering include scaling up the development of hydrogen technology, increasing the production of clean hydrogen to one million tonnes per year and doubling the funding for the hydrogen initiative within the EU budget to €1.3 billion (Kovač, Paranos & Marciuš, 2021). Other measures include allocating €2-4 billion over the next two years to launch projects financed by the sale of emission allowances and supporting investments in renewable energy and hydrogen infrastructure. According to the published documents, the overall EU economic package should include a plan for 2021-2027 and a "recovery instrument" of at least half a trillion euros (Vivanco-Martín & Iranzo, 2023).

One of the most promising concepts for the development of a hydrogen economy in Europe are the so-called hydrogen valleys. These are regional ecosystems within which hydrogen is produced, transported and used within an integrated system. Such areas could serve as a springboard for the creation of a larger European hydrogen economy (Sadik- Zada, 2021). Currently, there are only three hydrogen valleys in the EU - one in Denmark and two in Germany. These countries can be considered pioneers in this area. On the positive side, however, another 17 projects are actively developing, indicating a gradual expansion of hydrogen solutions across the European continent (Kumar & Lim, 2022).

1.1.2 European ambitions for hydrogen valleys

The European Commission has set itself an ambitious target of doubling the number of operational hydrogen valleys by 2025. The Commissioner for Innovation, Research, Culture, Science and Youth has highlighted their importance. According to her, hydrogen valleys are key to creating a European hydrogen research and innovation area. Hydrogen valleys allow new technologies to be integrated directly into a hydrogen ecosystem tailored to local requirements. This approach provides space for testing and optimizing different solutions before their wider deployment, which is extremely important for new and emerging technologies (Lagioia, Spinelli & Amicarelli, 2023).

1.1.3 Main challenges in the development of hydrogen technologies

The three main obstacles can be considered regulation, permitting processes and access to the energy grid. Countries need clear regulation and clear permitting processes, but access to the energy grid is the most problematic (Zainal et al., 2024). This is essential to ensure sufficient renewable electricity to produce green hydrogen. Without solving this problem, it will be difficult to achieve the set goals for the production and use of hydrogen on the required scale. These challenges reflect the complexity of the transition to a hydrogen economy (Kakoulaki et al., 2021).

While the European Union coordinates a common approach to the hydrogen economy, individual Member States are implementing their own initiatives that reflect their specific conditions, priorities and possibilities (Mneimneh et al., 2023). Germany and Denmark have emerged as European leaders in hydrogen technologies, as evidenced by the fact that these countries are home to three currently operational hydrogen valleys (Hashimova, 2023). Germany, Europe's largest economy, is investing massive resources in the development of the hydrogen sector, while Denmark is building on its experience with wind energy, which it plans to use to produce green hydrogen (van der Spek et al., 2022). In 2024, the European Commission, together with Spain, Lithuania and Austria, announced new financial support for the development of hydrogen from renewable sources through an innovation fund. These three Member States have joined the "Auctions as a Service" scheme in the second auction of the European Hydrogen Bank. In addition to the €1.2 billion in EU funding, the three countries have allocated over €700 million from national resources to support renewable hydrogen projects on their territory. The total funds mobilised through the renewable hydrogen auction reached around two billion euros (Falcone, Hiete & Sapio, 2021).

1.1.4 Technological and infrastructure constraints

Another major challenge is the need to develop and optimise technologies for the production, storage, transport and use of hydrogen. Electrolysers, the essential equipment to produce green hydrogen, are still relatively expensive and their production on an industrial scale is limited. The infrastructure for the distribution of hydrogen is also problematic (Squadrito, Maggio & Nicita, 2023). Although some European countries, such as the Netherlands, Germany and Portugal, have the potential to use existing natural gas infrastructure to transport hydrogen, this requires significant investment and technical adaptations. These countries are well placed to expand the use of hydrogen thanks to their natural gas infrastructure that can be adapted to transport hydrogen (Trattner, Klell & Radner, 2022; Azadnia et al., 2023). The economic viability of hydrogen projects remains one of the biggest obstacles to their wider deployment. The production of green hydrogen is currently more expensive compared to conventional methods of producing hydrogen from natural gas or the direct use of fossil fuels in industry (Capurso et al., 2022). Hydrogen currently accounts for less than 1 percent of European energy consumption and is mainly used as a feedstock in the chemical industry (Ismayilova & Hajiyeva, 2024). This situation highlights a significant gap between current reality and strategic objectives, underlining the need to accelerate the development of the sector and increase investment in relevant technologies and infrastructure (Seck et al., 2022; Genovese et al., 2023).

While there is a growing number of studies addressing the potential of hydrogen as part of a green transition (e.g. in industry, transport or energy), most research focuses on the technical, technological or environmental aspects of hydrogen use. However, only a limited number of works analyse regional differences in the development of hydrogen infrastructure in relation to the economic performance of countries. In particular, there is a lack of comparative analysis linking economic indicators such as GDP per capita with practical indicators of progress in hydrogen mobility and production. This study therefore seeks to fill this gap by examining whether and how a country's economic strength influences its ability to develop a hydrogen economy. Based on the identified research gap, we formulated the following research question: "What is the relationship between the economic maturity of countries (measured by GDP per capita) and the rate of development of hydrogen infrastructure, including the number of hydrogen vehicles and production capacities in EU-27 countries?".

2 DATA AND METHODOLOGY

This study examines the relationship between hydrogen infrastructure capacities and economic development in EU-27 countries. The dataset used includes national indicators obtained from publicly available sources such as Eurostat, the European Hydrogen Observatory and national statistical offices.

Three main variables were selected for the analysis:

- Hydrogen production capacity (MW/MWel),
- Hydrogen consumption capacity (in tonnes/year),
- GDP per capita (in euros).

Countries were divided into two groups – high and low levels of hydrogen infrastructure development – based on aggregated indicators of hydrogen production and consumption in 2025.

Due to the small sample size and the lack of examination of normal distribution, non-parametric tests were used to verify statistical differences between these groups:

- The Kruskal-Wallis test was used to assess differences between groups,
- The effect size (ε^2) was calculated to estimate the significance of the differences,
- Subsequently, Dwass-Steel-Critchlow-Fligner pairwise comparisons were applied to identify specific differences between groups.

The chosen methodological approach allowed comparing the readiness for the implementation of hydrogen solutions in different economic contexts, while taking into account the limitations of the available data and their distribution.

Based on the research question, we formulated the following hypotheses:

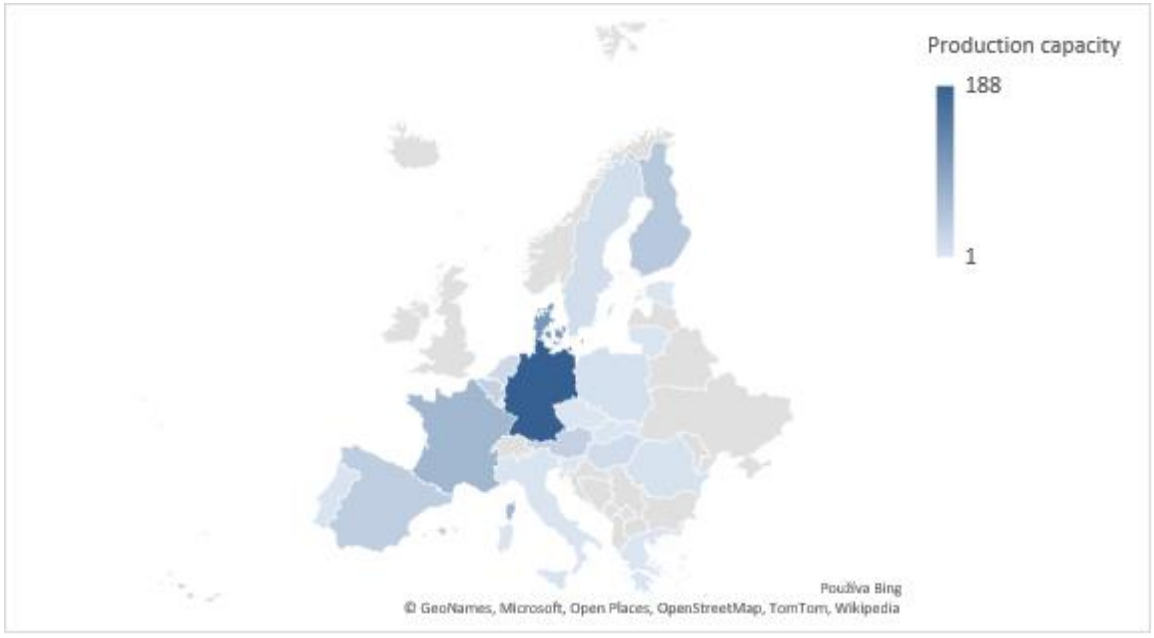
H1: *There is a statistically significantly higher hydrogen production and consumption capacity among countries with higher GDP per capita compared to countries with lower GDP per capita*.

H2: *Countries with higher GDP per capita have a higher number of registered hydrogen cars compared to countries with lower GDP per capita*.

3 RESULTS AND DISCUSSION

Figure 1 shows the differences in hydrogen production capacities between EU-27 countries. The results show higher production capacity in economically stronger countries, which corresponds to their investment potential and technological maturity (Germany, France, Denmark, Finland).

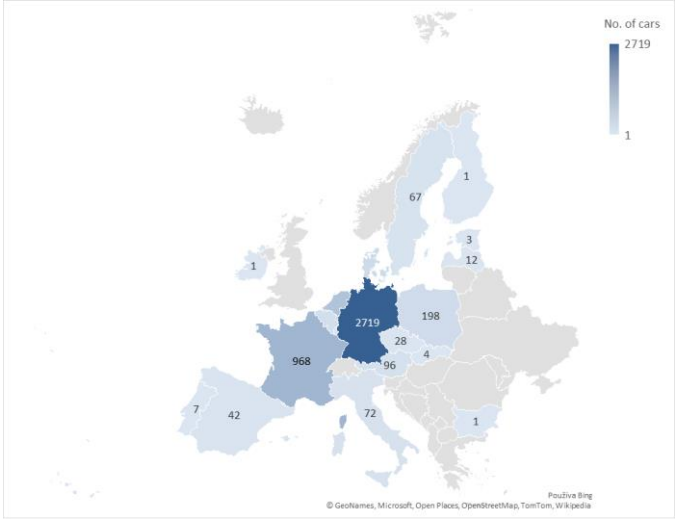
Figure 1. *Production capacity in the European union (2025)*



Source: European Hydrogen Observatory (2025)

Figure 2 illustrates the current number of registered hydrogen-powered passenger vehicles in individual European Union member states. Countries such as Germany and France have the highest number of registrations, indicating their more active approach to supporting alternative transport fuels and developing hydrogen infrastructure.

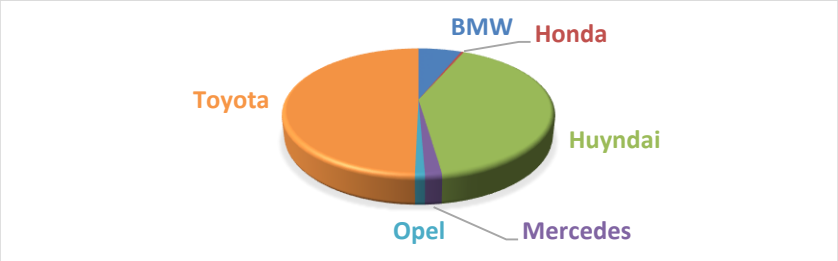
Figure 2. *Number of registered hydrogen cars in the European union*



Source: European Hydrogen Observatory (2025)

Figure 3 shows the market share of different car brands offering hydrogen-powered vehicles in individual European Union member states. The dominance of brands such as Toyota and Hyundai highlights the technological leadership of Asian manufacturers in the field of hydrogen propulsion and their penetration into the European market.

Figure 3. *Brand share of registered hydrogen cars in the European union*



Source: European Hydrogen Observatory (2025)

The results of the analysis show that there are statistically significant differences in the three variables under study between groups of countries with high and low levels of hydrogen infrastructure development: hydrogen production capacity, hydrogen consumption capacity and GDP per capita.

Table 1: *One-way ANOVA results*

	χ^2	df	p	ε^2
Production_capacity	6.1372	1	0.0132	0.3230
Consumption_capacity	5.7130	1	0.0168	0.3007
GDP_per_capita	10.5657	1	0.0012	0.5561

Dwass-Steel-Critchlow-Fligner pairwise comparisons

Pairwise comparisons - Production_capacity

		W	p
High	Low	-3.5035	0.0133

Pairwise comparisons - Consumption_capacity

		W	p
High	Low	-3.3802	0.0169

Pairwise comparisons - GDP_per_capita

		W	p
High	Low	-4.5969	0.0012

These results confirm that countries with higher GDP per capita also have significantly more developed hydrogen infrastructure – both higher production and consumption capacity. This trend is consistent with findings from previous studies that suggest that economically stronger countries are better positioned to invest in new technologies, including hydrogen (Capurso et al., 2022).

These differences suggest that the development of a hydrogen economy is closely linked to a country's economic performance. Rich countries such as Germany, Austria, and Denmark invest in the so-called "hydrogen valleys" – integrated regional ecosystems where hydrogen is produced, distributed and consumed locally (Lagioia et al., 2023).

On the contrary, in countries with lower GDP and weaker infrastructure, the development of these technologies faces a number of obstacles. The main ones include regulatory barriers, complex permitting processes and limited access to energy networks (Zainal et al., 2024).

An important finding is also the fact that high GDP does not automatically guarantee increasing hydrogen consumption – for example, Germany shows a decreasing trend in the volume of biofuel consumption, which may be related to the diversification of renewable sources and the streamlining of production processes (van der Spek et al., 2022).

The obtained results confirm that the development of hydrogen infrastructure is significantly influenced by the economic strength of the country. To achieve the EU's green economy goals, it will therefore be crucial to create support tools for less developed countries so that they can effectively participate in Europe's energy transformation (Falcone et al., 2021).

The results of the analysis clearly support both hypotheses and indicate that the economic maturity of countries is a significant determinant of the development of hydrogen infrastructure. Countries with higher GDP per capita achieve higher hydrogen production and consumption capacity, as well as a larger number of registered hydrogen vehicles. This trend is consistent with the findings of previous studies (Capurso et al., 2022; Lagioia et al., 2023) and points to the need for specific support instruments for less developed EU Member States. At the same time, it was identified that economic maturity alone may not be a sufficient prerequisite for the intensive use of hydrogen, as consumption can also be influenced by the diversification of the energy mix and the structure of industry in the countries concerned.

Table 1 clearly confirm the statistical significance of the differences between groups of countries. A p value of < 0.05 for all three variables (production capacity, consumption and GDP per capita) together with an effect size of ε^2 above 0.3 indicates a moderate to strong effect. These results are consistent with the assumption that economically stronger countries have a higher level of technological readiness as well as better access to investment resources.

4 CONCLUSIONS

This paper highlights significant differences in the development of hydrogen infrastructure between European countries and confirms that economically stronger countries (with higher GDP per capita) achieve higher hydrogen production and consumption capacity. The strength of the research

is the use of non-parametric statistical methods, which are also suitable for smaller samples and non-ideal data distribution, which allows for robust comparisons between groups of countries.

On the other hand, the study is limited by the relatively small number of countries analysed and the focus on selected quantitative indicators only. Therefore, the results cannot be generalized without reservations to the entire EU. In addition to economic maturity, other factors can also influence the development of hydrogen infrastructure – for example, the availability of natural resources, energy policy, public perception of hydrogen technologies or the level of technological readiness (compare with van der Spek et al., 2022; Capurso et al., 2022).

The practical implications of the research are clear – if the hydrogen economy is to be a tool for a fair and environmentally sustainable transformation of Europe, it is essential to specifically support the development of infrastructure, including in economically weaker countries. Policies should focus on: widening access to investment through European funds; simplifying permitting processes; supporting research and development of local solutions (Zainal et al., 2024); strengthening education and raising awareness about hydrogen in society.

In the future, research should follow longer-term developments and expand the spectrum of variables, including environmental benefits and socio-economic effects of the introduction of hydrogen technologies. It is also important to analyse in more depth successful examples, such as the so-called "hydrogen valleys" in Germany and Denmark, which could serve as a model for other countries (Lagioia et al., 2023).

The paper summarizes the knowledge on the development of hydrogen infrastructure in EU Member States and confirms the importance of economic maturity as a key factor in this development. The results point to the need for a differentiated approach to the creation of public policies that would take into account regional specificities and support the implementation of hydrogen solutions also in less developed areas. Specifically, countries with a GDP per capita above EUR 35,000 showed on average twice the hydrogen production capacity compared to countries whose GDP did not exceed EUR 20,000. In the future, it is appropriate to expand the research to include qualitative aspects, as well as environmental and socio-economic consequences of the introduction of hydrogen technologies.

In conclusion, it can be stated that the support of the hydrogen economy must be systemic, inclusive and strategically coordinated at the EU and individual national levels in order to fulfill its transformative potential in the context of a green economy.

The practical implications of the study lie in identifying specific economic obstacles that limit the development of hydrogen infrastructure in less developed countries. The results provide an argumentative basis for creating targeted financial and technical support from the EU, for example through cohesion policy, the European Hydrogen Bank or programs focused on regional innovation. At the same time, the contribution points to the need to simplify permitting processes and strengthen interstate cooperation in building hydrogen ecosystems. Taking these factors into account can contribute to a more balanced and effective implementation of the goals of the European Green Deal.

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